Renewable and Sustainable Energy Reviews 15 (2011) 1305–1313

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

An introduction to the life cycle assessment (LCA) of bioelectrochemical systems (BES) for sustainable energy and product generation: Relevance and key aspects

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ARTICLE INFO

Article history:
Received 7 June 2010
Accepted 14 October 2010

Keywords:
Microbial fuel cells (MFCs)
Bioenergy
Life cycle assessment (LCA)
GHG balance
Wastewater
Economic analysis

ABSTRACT

Bioelectrochemical systems (BESs) are devices capable of converting organic waste fraction present in wastewaters into useful energy vectors such as electricity or hydrogen. In recent years a large amount of research has been done on these unique systems in order to improve their performance both in terms of waste treatment as well as electric current production. Already there are plans to upscale this technology to convince the end-users of its potential. However, there are not many studies available on the life cycle of these systems with the current state of the art. In this article a methodology has been proposed to perform the life cycle assessment (LCA) of the BESs and some recommendations have been given which may be useful in carrying out LCA of these systems. Not only the direct benefits in terms of energy saved in aerating the wastewater treatment plants, but also the resulting saving in cost and electric power produced should be factored as well. The results of LCA should show that with current knowledge and existing materials, how well the MFCs compares with the existing treatment methods such as anaerobic digestion. Further, given the amount of research going on in this field, it is expected that with cheaper materials and better microorganisms, the technology will breakthrough even soon.

Contents

Abbreviations: AC, activated carbon; AD, anaerobic digestion; AOP, advanced oxidation processes; BAT, best available technologies; BES, bioelectrochemical systems; BOD, biological oxygen demand; CDM, clean development mechanism; COD, chemical oxygen demand; GHG, green house gases; LCA, life cycle assessment; MDC, microbial desalination cell; MEC, microbial electrolysis cell; MFC, microbial fuel cells.

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doi:10.1016/j.rser.2010.10.005

1. Introduction

Current worldwide annual energy demand is approximately 13 terawatts (TW), and an additional 10 TW of energy to maintain current lifestyles will be needed by 2050 [1]. Worldwide the search is on for renewable energy sources due to various benefits associated with their use viz. decreasing import dependency, diversifying sources of production, and contribution to sustainable development [2]. This has placed attention on the utilization of fermentable sugars from lignocellulose, the largest known renewable carbohydrate source [3], for biofuel production. However, plant derived biofuels in particular, have a bad press both in terms of competition with good agricultural land for food, and also in terms of the associated energy balance with the whole life cycle analysis of the biofuel system [4]. At the same time, environmental pollution from municipal, industrial and agricultural operations/wastes continues to grow. The concept of the 'four Rs', Reduce, Reuse, Recycle and Renewable energy, has generally been accepted as a useful principle for waste handling [5]. Further, it has been suggested that reuse is (normally) environmentally better than recycling, recycling better than incineration with energy recovery, and incineration better than disposal [6]. The potential of sugar crops, agro and urban/industrial residues feedstocks for production of ethanol as an alternative, renewable, sustainable, efficient, and environmentally safe fuel has already been demonstrated [7,8].

1.1. Bioelectrochemical systems

Bioelectrochemical systems (BESs) are novel technologies based on the ability of certain microorganisms to catalyze an oxidation and/or reduction reaction at an anodic and cathodic electrode, respectively [9]. BES technology promises to replace energy intensive wastewater treatment processes, produce sustainable energy from wastewaters, and produce chemical products [10]. Depending on the mode of operation and end product formed, BESs can be further categorized into microbial fuel cell (MFC), microbial electrolysis cell (MEC) and more recently microbial desalination cell (MDC) [11]. The interest in these technologies is so high that already terms such as 'microbial biorefineries' are being used to describe the systems based on them [12,13]. The microbial biorefinery could be the next step in the already existing green biorefinery, forest and lignocellulosic biorefinery, aquatic or algal biorefinery and integrated biorefinery concepts [14].

1.2. Life cycle assessment

In order to identify savings in energy and emissions from any type of bioenergy production and use, a thorough evaluation from "cradle to grave" must be carefully carried out [15]. Life cycle assessment (LCA) has been the method of choice in recent years for various kinds of new technologies for bioenergy and carbon sequestration. LCA is an universally accepted approach of determining the environmental consequences of a particular product over its entire production cycle. This systematic approach will eventually reveal the true potential of the product evaluated and identify the environmental hot spots in the product chains so that precautionary steps can be suggested to reduce the negative environmental impact [16]. Thus, LCA is a method to define and reduce the environmental burdens from a product, process or activity by identifying and quantifying energy and materials usage, as well as waste discharges, assessing the impacts of these wastes on the environment and evaluating opportunities for environmental improvements over the whole life cycle [17]. Recently, LCA was used to estimate the energy and climate change impacts and the economics of 'biochar' (stable, carbon rich charcoal resulting from pyrolysis of biomass materials) systems [18]. Similarly, a comparison of algae to other bioenergy feedstocks based on LCA was presented by Clarens et al. [19]. LCA is thus necessary to avoid unintended consequences of a new technology or mitigation strategy.

1.3. Technological background

With every new technology it is important that its environmental footprints are very clearly marked before it is applied on a large scale. It is even more important for the case of bioenergy systems because bioenergy technologies use renewable biomass resources to produce an array of energy related products including electricity, liquid, solid, and gaseous fuels, heat, chemicals, and other materials. For example, it is widely believed that algae could be important source of biofuels as they do not take up valuable farmland, and hence do not threaten food supplies. However, very recently, Clarens et al. [19] modelled the environmental impacts of algal farms and concluded that they require six times as much energy as growing land plants and emit significantly more greenhouse gases (GHGs). Bioelectrochemical systems (BESs) have gained a lot attention in recent years with both in terms of number of researchers as well as the applications for these systems [20]. Even though, the research so far has been limited to lab-scale reactors with volumes ranging from few micro litres to several hundreds of millilitres, it is expected that in coming years, the commercialization of the technology on larger scale would be possible [21]. So far, the only MFC type that has been used for practical applications is sediment MFC which harvest power from sediment by embedding an anode in sediment and connecting it via an electrical circuit to a cathode placed in the overlying aerobic seawater, making it feasible to power on-site to sensors and telemetry devices in remote oceanic areas [22]. However, to avoid unintended consequences of the new technology, it is necessary to conduct analyses of potential lifecycle impacts of bioelectrochemical systems. A detailed economic analysis of MFCs has not been reported to date [23]. Considering the rapid growth in the research on MFCs and increasing electric current and power from these systems, it is only a matter of time before these systems are scaled up. Already a few efforts on pilot-scale have been made [24]. A pilot MFC to treat brewery wastewater was installed and operated in Australia [25]. Recently, a pilot microbial electrolysis cell (MEC) was started at Napa valley, California to treat winery wastewater [21]. Plans for a pilot MFC are already underway at Saudi Arabia (Logan, B.E., personal communication). Some of these ongoing pilot tests were recently reviewed by [21] with an emphasis on building, operation, materials used in these systems.

1.4. Aim of the paper

Despite the proliferation in efforts on scaling-up the BESs, there has not been any evaluation of BESs with regard to their life cycle in terms of performance as well as comparison to existing technologies which they want to complement or augment. Therefore it is very important to have a complete "cradle to grave" life cycle assessment of these systems. This will not only give an idea to the researchers and policy makers of all the necessary technical/scientific points which should and must be considered before scaling up these systems but also serve as a guiding tool to the practitioners of this technology. The lifecycle concept is an integrated approach that incorporates the environmental and economical impacts of all stages in a production chain; it has been applied to an increasing number of conventional and renewable energy generation systems [26]. Thus this paper aims to compile an inventory of inputs and outputs of microbial fuel cell (MFC) in order to help researchers to evaluate, compare and validate the feasibility of this emerging technology. Further, it also summarizes the factors which must be taken into account by researchers while up-scaling these systems as well as key issues for quantifying the use of resources

and releases to the environment associated with the entire life cycle of BESs.

2. Goal definition, scope and functional unit of the study

Any LCA study involving BESs should clearly define the goal, scope and functional unit as the primary steps of the study. For example, the goal could be presenting the current scenario for converting wastewater to useful energy using BESs. This can be then compared with the conventional anaerobic digestion (AD) technology for biomethane production from wastewater on the life cycle energy balance and environmental consequences, such as wastewater treatment and potential GHG emissions saving. The goal of the MFC energy, GHG and economic LCA should be to quantify the energy, GHGs and economic flows associated with the BES systems for a range of feedstocks.

The scope should be sufficiently well defined to ensure its compatibility with the goal. The scope of LCA could be to evaluate the environmental performance of BESs, the novel systems for conversion of organic waste directly into electricity. The analysis can be divided into three stages: wastewater treatment, electricity generation and chemical product formation.

Functional unit sets the scale for comparison of two or more products, provides a reference to which the input and output data are normalised and harmonises the establishment of the inventory [27]. The primary purpose of the functional unit is to provide a reference to which the inputs and outputs are related and is necessary to ensure comparability of results [28]. The functional unit, depending on the goal of the study, must be expressed in terms of per unit output basis [4]. However, the definition of the functional unit is a special issue for LCA studies of waste management options, since LCA for waste management differs from product LCA. In an LCA for waste management the functional unit must be defined in terms of system's input, i.e., the waste. The management of the quantity of specific waste, or the waste of one household, or the total waste of a defined geographical region in a given time (e.g., 1 year) can be chosen as the functional unit [29]. Thus, if the BES is being projected as a wastewater treatment tool, then the functional unit will also change accordingly. In that case it could be treating 100,000 m^3 wastewater/d with 2000 mg/L BOD [30]. Thus the emphasis is placed on a functional unit representative of a 'service' provision (that of cleaning wastewater) where the main objective is to achieve a satisfactory onward provision of water at a quality acceptable to potential markets. The functional unit for MFCs can be chosen as 1 kW electricity/m^3 of anode volume as this is the output level from MFCs at which they are assumed to be competitive to anaerobic digestion [31]. Moreover, this unit enables comparison of all tested reactors, not only within the existing studies but also with other existing bioconversion technologies [32]. However, if electric current generation alone is the goal of MFCs independent of the substrate, then a better unit would be current generated per unit area of the electrode surface area (mA/cm^2) or current generated per unit volume of the cell (mA/m^3) [20]. It can be assumed that in case of MEC also, the resulting hydrogen will be converted into electric energy and the same functional unit can be used there as well. Similarly, for product formation the target of 1000 A/m^3 should be met [33,34]. Further, the environmental impacts in terms of GHG emission saving should be expressed as gCO_2 equivalent (CO_2e)/MJ energy replaced [35]. The environmental impacts can be expressed as gCO_2e emission from treatment of 1 m^3 waste water.

3. System boundaries

The goal and the scope of the study will determine the initial boundaries of the system. Inputs and outputs in unit processes are linked within the boundaries of the system. A uniform and clear determination of system boundaries should accurately estimate the possible environmental impacts other than GHG emissions between LCA for renewable fuels and conventional fuels [36]. An LCA should track all the processes in the life cycle of the product system, but in practice, due to the lack of readily accessible data, it may not be feasible. This becomes even more true in case of BESs as most of the studies so far have been limited to lab-scale systems and the results for few pilot-scale demonstrations are only coming in now. Concepts such as 'well to tank' [37], 'well to wheel' or 'cradle to grave' [38] are also difficult to apply to BESs because their most likely large scale application at this moment seem to be in wastewater treatment, thus omitting the need for transporting the generated energy [30]. It is foreseen that the electricity produced in MFCs by treating the wastewater or different fuels like sugar, fruit, dead insects, grass and weed can be used locally for other applications such as biologically inspired robots or Gastrobots [39,40]. Similarly, the electricity could also be used for the electrolysis of water or, more efficiently, hydrogen could be produced directly from biomass sources using the bio-electrochemically assisted microbial reactor (BEAMR) process [41], this makes the whole BES process a cradle to cradle system.

In MFC, microorganisms oxidize organic matter in the anode chamber (anaerobic conditions) producing electrons and protons. Electrons transfer via the external circuit to the cathode chamber where electrons, protons and electron acceptor (mainly oxygen) combine to produce water [42]. Microbial electrolysis cells require energy input, but they can produce products, such as hydrogen gas [43] and hydrogen peroxide [44]. Using the electrolysis cells, the products could be created sustainably at a lower energy cost at the treatment plant. An overall scheme of BES process and its possible system boundary for LCA is shown in Fig. 1.

If the ambition of the LCA is to compare BES with the conventional technology like anaerobic digestion (AD), then the fact must be taken into account that while anaerobic digestion can be applied to treat high strength substrate (with more than 1 g COD/L), the MFC application niches can be found in the area of treating low concentration COD substrates and at low temperatures (10–20 °C), i.e., where AD does not function well [45].

4. Reference system

Assuming that the main goal of BESs is to treat wastewater, then there has to be a reference system against which the performance could be measured. At this moment, anaerobic digestion seem to be the ideal reference system both in terms of performance as well as costs against which the performance and cost of BESs can be evaluated [45,46]. Similarly, in case of hydrogen production in MEC, an ideal reference system could be another biological system such as algal photobioreactor for which the material costs and net energy ratio have already been described in detail [47]. For MFCs the final energy efficiency must be considered on a per unit volume of wastewater treated as it is important to maximise the final output in terms of wastewater treated as well as power produced.

5. Process inventory

The inventory, background of the data, calculation and assumptions for this analysis should be discussed in this section. Microbial fuel cells (MFCs), the primary manifestation of BESs, were used to produce power from the electric current generated by the bacteria. However, there has been tremendous evolution in these systems for various other applications as well [48]. Not all the processes taking place in a BES are thermodynamically favorable. Among the different reactions in BES, most are thermodynamically favor-

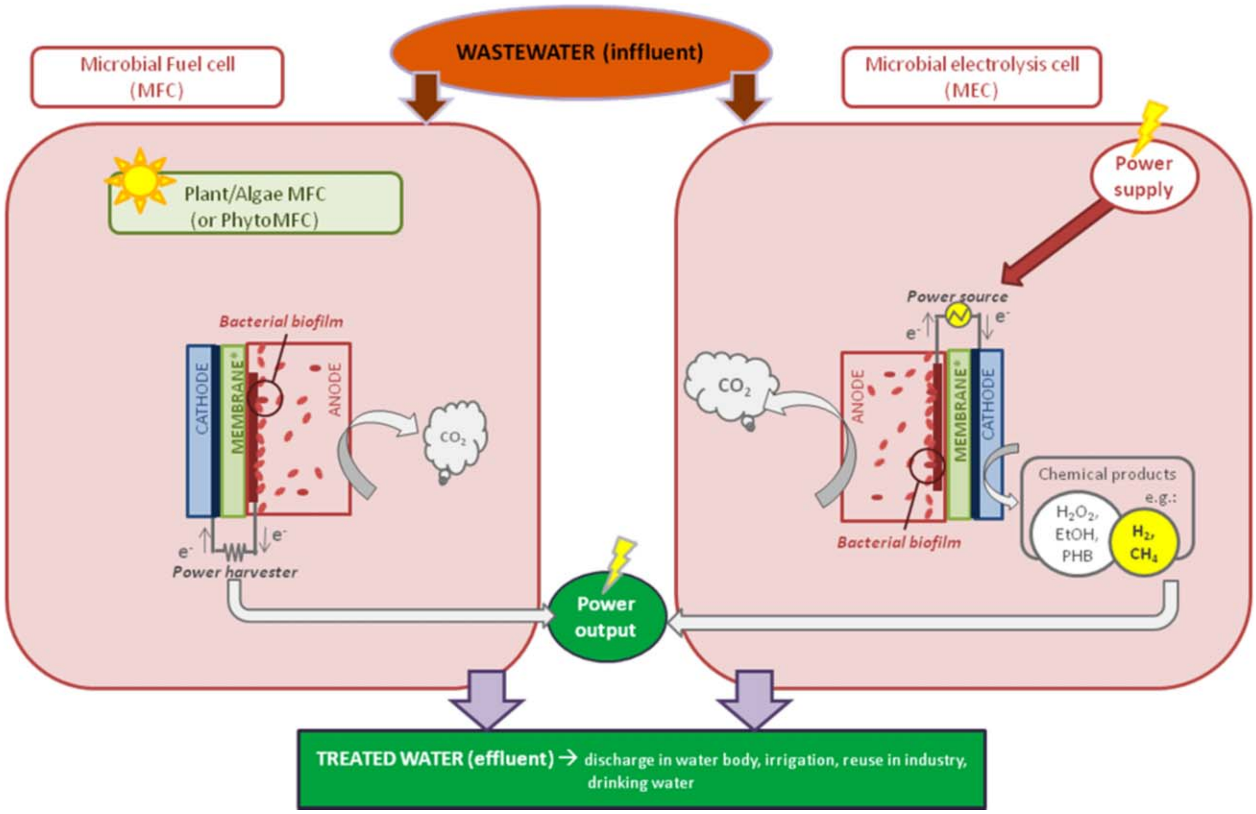


Fig. 1. An overall scheme showing the different aspects of bioelectrochemical systems. The solid pink line indicates the system boundary.

able except the production of hydrogen and ethanol which are electricity consuming reactions [49,50]. Carbon dioxide capture and conversion to useful compounds in a MFC is another lucrative application, that has partly been realized recently [51]. These authors reported the possibility of direct electron transfer between a cathode and microorganisms for fixation of CO_2 in biomass. In another specialized application of this technology, MEC was used for direct reduction of CO_2 to methane using a biocathode containing methanogens [52]. These researchers reported that the Archaea, using the same electrical voltage input as needed for hydrogen production in MEC, could convert CO_2 and water to methane without any organic material, bacteria or hydrogen normally found in MEC.

Existing wastewater treatment facilities, while treating wastewater to a quality deemed safe for discharge, also consume considerable energy during their operational life, and consequently contribute to atmospheric carbon dioxide and other GHG emissions. However, it has been stressed that selection of a particular wastewater treatment technology should not be based primarily on technical insight, but should also integrate the human and environmental activities that surround it. This holds equally true for emerging technologies such as BESs [53].

While determining the energy efficiency of a renewable energy source, all the energy inputs and outputs need to be considered [54]. Energy efficiency of BESs can be defined as the energy output of the BES over the energy input [48]. This energy could be in the form of electrical energy and/or chemical energy. The electrical energy produced in MFCs vary considerably and is affected by a number of factors such as type of substrate, conductivity of the solution, the inoculum, electrode materials, reactor design, operating conditions (temperature, external loading, etc.). Most of the lab studies used a pure compound like acetate or glucose as substrate [55–57]. Other waste resources that can act as promising substrates are livestock manure such as poultry and cattle, industrial wastewater from breweries [20,30]. However, some of these substrates might need pre-treatment; for example, the brewery wastewater needs to be improved in conductivity before it can be used in MFCs. Concerning the anode material itself, Qiao et al. [58] reported that the use of nanostructured materials can significantly enhance the current density and power density of MFCs, which results from the increasing active surface area and fast charge transfer rate. Biocompatible nanomaterials are promising candidates for anode catalysis in MFCs, which possess sound surface physicochemical properties for strong cell adhesion, and bacteria-favoring pore structures, allowing their growth without blocking the food (fuel) transport channels while still a rendering high specific surface area.

The use of membrane/separator is essential as it leads to cleaner products, coulombic efficiency is higher and cathodic recovery of products is higher [48]. However, use of membrane leads to the development of a pH gradient between the anode and cathode resulting in an overall decrease in cell potential. Harnisch and Schröder [59] summarized the conflict of selectivity versus mobility related to migrative and diffusive transfers across a separator and concluded that at present there is no ideal method for separation of an anode and cathode.

6. Co-product, by-product and residue

According to Clean Development Mechanism [60] co-products are defined as products with similar economical revenues to the main product, by-products are products with lower revenues than that of the main product whereas wastes have little or no revenue. In case of BESs, apart from treating wastewater several other products can be generated at cathode such as hydrogen [49], methane [52], hydrogen peroxide [44] or ethanol [50] by slightly altering the design and supplying additional voltage. The different output products for BESs are shown in Table 1. Besides, MFCs were used recently in a specific configuration for simultaneous water desalination and electric power generation [11]. An important challenge

Table 1
Types of BESs and the products formed in them.

BES type	Product formed	Maximum value reported	Comment	Reference
MFC	Electricity (Power density)	3.9 W/m^2	An adapted strain of *Geobacter sulfurreducens* KN400 with acetate (10 mM) substrate in a 2-chamber MFC	[61]
		2.77 W/m^2	Glucuronic acid (6.7 mM) was the substrate with mixed bacterial culture in an air cathode MFC	[62]
MEC	Hydrogen	2 $m^3\ H_2/m^3/d$	P-glycerol as substrate in 1-chamber membraneless MEC	[63]
MEC	Methane (CH_4)	0.75 L/L MEC/d	Acetate as substrate in a 2-chamber set up and a applied cell voltage of -0.813 V	[64]
MEC	Hydrogen peroxide (H_2O_2)	1.9 $kg/m^3/d$	Acetate (1 g/L) as substrate in a 2-chamber set up with mixed microbial consortium	[44]
MEC	Ethanol	1.26 $mmol/m^3$ cathodic compartment/d	Reduction of acetate to ethanol in a 2-chamber set up using mixed culture inoculums and methyl viologen as mediator	[50]

for biorefineries, is to handle the large amounts of wastewater streams generated by the process [65]. Recently MFCs were integrated in a cellulosic ethanol biorefinery for removing fermentation inhibitors resulting in higher ethanol yields at high biomass loading, improved water recycle and electrical power production up to 25% of total biorefinery power needs. A sustainable solution for removal of the residual organic matter in the effluents from bioethanol and biohydrogen processes is to convert them to biogas and use the residual effluents as fertilizers on agricultural soil [66]. This approach could also be applied to the treated water (effluent) originating from BES processes.

7. Impact assessment

The potential of BESs in relation to GHG emissions must be factored in while performing an LCA of these systems. Impact assessment establishes a relationship between the product or process and its potential impacts on human health, environment and sources depletion [67]. In case of MEC where the hydrogen is the main end product, the storage and transport should be factored in. As it is impractical to store or transport hydrogen at atmospheric pressure, due to its low volumetric energy density, the energy required to compress and store the hydrogen should be included as an input to the biohydrogen system. This input includes the energy content of the compression and storage infrastructure [47].

For plant MFCs, the potential for GHG sequestration should be taken into account. For example, the rice paddies are the second most important 30% emitter of methane [68], which has a global warming potential (GWP) 21 times that of CO_2 over a hundred years time horizon [69]. However, if the idea of using living plants as MFCs become successful and the target of low GHG emission is achieved in such a system, then this benefit of reduced GHG must be taken into account while performing the LCA [70].

Another important saving in energy and eventually in reduced GHG emission could be in the wastewater treatment processes when BESs are used there. Biological treatment is nowadays considered to be among the best available technologies (BAT) for wastewater treatment [71]. Advanced oxidation processes (AOPs), are the methods based on the in situ production of transient radical species of great oxidant power, specially hydroxyl radicals (OH^-). The potential of AOPs for destroying almost any organic contaminant is widely recognised, but it is also known that they entail higher costs as compared to biological treatment, due to an intensive use of energy and expensive reactants [72]. Most wastewater is currently treated using a process called "activated sludge", in which air is pumped into waste for oxygenation. This aeration process is extremely energy-intensive [73], and wastewater treatment expends as much as 67 percent of its energy in this aeration step alone [74]. A comparison of BESs with conventional wastewater processes such as activated sludge and anaerobic digestion is given in Table 2.

Addition of buffer salts (like phosphate and carbonate) to anolyte or catholyte is not practical for large-scale applications such as a MFC based wastewater treatment. Apart from the environmental effects of feeding such amounts of chemicals into wastewater treatment (resulting in increased CO_2 into atmosphere), such a concept is noneconomic [59]. However recently it has been shown that carbon dioxide (CO_2) can be added to the air-cathode to buffer the pH shift between anode and cathode [77,10]. This addition of CO_2/bicarbonate is a better option than adding phosphate buffer which might require subsequent removal prior to discharge. Also, CO_2 is the end product of MFC which can be directly used in the system for buffering purpose, thus no external CO_2 feeding is necessary.

Another important aspect to be considered is the end-of-life options for BESs once these systems have reached the end of their useful life. Then the recycle and reuse options must be considered based on technical, economic and environmental feasibility. For polymer electrolyte membrane fuel cell (PEMFC) end-of-life options based on the electrolyte, electrocatalysts, bipolar plates and ancillary components were described [6]. Similar approach of BESs could lead to an improvement in their overall environmen-

Table 2
A comparison between the BES technology with a conventional treatment systems (aerobic treatment and anaerobic digestion).

Parameter	Activated sludge	Anaerobic digestion	BES technology
Direct conversion of substrate energy to electricity	None	Medium	High conversion efficiency
Energy consumption	0.7–2 kWh/kg COD	Low	0.5–2.4 kWh/kg COD for MEC; None for MFC
Energy input for aeration	Very high	None	None
Operational temperature	Ambient	Mesophilic and termophilic	Ambient and low temperatures
Gas treatment	Low	Required	None off-gases in BESs are enriched in CO_2 with no useful energy content
Sludge production	High	Low	Low
Loading rate (kg $COD/m^3/d$)	0.5–2	8–20	6.5 for MEC; 3.3 for MFC
Nutrient removal	Yes	No	Possible
Possibility of remote island application	Low	Low	High potential

Refs. [32,43,75,76].

Table 3
Cost estimates for BESs and its components over the years.

Year	Proposed Price	Remark	Reference
2006	€4000/m^3 of electrode compartment	This capex cost was estimated to be at a level 10 times that of anaerobic digestion	[32]
2008	€2025/m^3	This include cost of graphite felt anode, platinum catalyzed cathode, membrane, current collector, reactor volume	[46]
2010	€2816/m^3	This price was calculated from the estimates of a full-scale MFC system treating 100,000 m^3 wastewater/d in 1667 individual MFCs of 20 L anode volume	[30]
2010	€1137/m^3	This include cost of activated carbon anode, non-platinised cathode, membrane, current collector, reactor volume	[85]

tal and economic aspect during LCA. Very recently, Foley et al. [34] reported on the LCA of high-rate AD, MFCs and MECs. These authors concluded that MFC does not provide a significant environmental benefit relative to the "conventional" AD option. However, a MEC provides significant environmental benefits through the displacement of chemical production by conventional means.

8. Economic analysis

Most of the conventional methods of water disinfection, decontamination and desalination are often chemically, energetically and operationally intensive, focused on large systems. Thus, they require considerable infusion of capital, engineering expertise and infrastructure, therefore precluding their worldwide usage [78]. There is an urgent need for new, sustainable, affordable, safe and robust methods to increase supplies and purify water. MFCs offer an excellent choice for wastewater treatment offering the dual advantage of giving energy simultaneously.

A fair assessment when comparing different renewable technologies requires consideration of both energy efficiency (ability to convert renewable energy into mechanical work or electricity) and the efficiency of construction materials and equipment exploitation [79]. In recent years, some researchers have tried to give an economic evaluation of the BESs in terms of their performance as well as the potential savings in the costs if these systems are used for wastewater treatments. A comparison of BES technology with anaerobic digestion was given by Pham et al. [45] and Rozendal et al. [46]. Powell and Hill [13] reported an economic feasibility study in which they demonstrated the possibility of integrating photosynthetic microalgae MFC that capture CO_2 and generate electric power and oil for biodiesel into an existing bioethanol production facility. Very recently, Fornero et al. [30] presented a first ever economic evaluation of MFC for revenue from electricity generation and municipal waste treatment cost. According to their calculation, for 100,000 L/d wastewater with a 2000 mg BOD/L and a coulombic efficiency of 20%, the net present value equals US$ 380,528 or $ 228/20-L MFC for a 10 year time span. In comparison, the cost to treat same wastewater stream at a municipal wastewater treatment plant with activated sludge tanks (secondary treatment) is $ 32,760 per year. The similar cost justification for MFC turned out to be US$ 35,731 per year.

The material costs of the main stack components are a decisive factor in the success of BES technology. In an MFC, the aeration costs are eliminated by using a cathode exposed directly to air. However, one of the reasons for the existing high cost of BESs is the use of expensive platinum (Pt) as a catalyst is the electrodes, sometimes up to a loading rate of 0.5 mg/cm^2 of electrode surface area [80]. To overcome this high cost, alternatives to Pt have been explored in recent years. These include CoTMPP (0.6 or 1.2 mg/cm^2) [81], iron phthalocyanine (1.0 mg/cm^2) [82], manganese dioxide (MnO_2) [83]. While these catalysts greatly reduce the cathode costs compared to Pt, the high loading needed to equal the performance of Pt can result in high overall costs. An inexpensive activated carbon (AC) air cathode was reported recently as an alternative to a platinum-catalyzed electrode for oxygen reduction in a MFC [84,85]. For MEC, Selembo et al. [86] recently reported the use of nickel powder as cathode catalyst which allows for much more cost-effective cathode components ($2.82/$m^2$ at a loading rate of 60 mg per 7 m^2 compared to $70/$m^2$ for the same platinum loading).

The second important factor contributing to high costs in BESs is the use of sophisticated proton exchange membranes such as Nafion® [59], which are expensive (approximately €1166/m^2 for Nafion®117) [87] and have several problems associated with them such as oxygen leakage from cathode to anode, substrate loss, cation transport and accumulation rather than protons, and biofouling [88]. To overcome these problems, the use of cloth separator (J-cloth, JC) between the electrodes was proposed [89]. The use of low cost Zirfon® separator to replace conventional Nafion® has also been proposed [85].

Another factor adding to the costs of these systems is the use of non-sustainable phosphate buffer electrolytes in order to minimize the pH imbalances between anode and cathode, which contribute to BES potential losses and therefore power losses [90,91].

Table 3 shows the cost estimates for BESs and its components as suggested by various researchers over the years. Thus, at present, the primary barriers to the economic viability of the BESs in general and MFCs in particular are the high cost of the electrode and membrane. An integrated system of MFCs using low-cost materials with conventional WWTPs may bring the desired advantages that overcome the present limitations in these systems and should be the focus of future LCA studies. To make the BES technology economically viable, the capital costs of construction must be kept as low as possible.

9. Allocation

Allocation refers to the distribution of environmental burdens between co-products in the LCA of a multifunctional system [92]. The broad perspective of LCA makes possible to take into account the significant environmental benefits that can be obtained through different waste management processes. Besides electricity and specialty chemical products, BESs can be used to remove specific pollutants from the wastewaters, mostly with simultaneous electricity production. These include denitrification [93], sulfur-based pollutants removal [94], reduction of Cr^{6+} [95]. Similarly, when ethanol was the main product in the BES from the reduction of acetate in the cathode compartment of a BES, there was a coproduction of hydrogen as well [50].

To summarize, bioelectrochemical systems with simultaneous electric power generation, wastewater treatment and co-product recovery have potential for renewable energy generation CO_2

Table 4
Details of companies based on MFC technology.

Company	Country	Website	Contact
Trophos Eenergy	USA	http://www.trophosenergy.com/	marcus.gay@trophosenergy.com
Lebone	USA	http://www.lebone.org/ For their work in Africa using MFC, read – http://www.lebone.org/the-innovation/	hello@lebone.org
Emefcy	Israel	http://www.emefcy.com/	info@emefcy.com
IntAct Labs LLC	USA	http://www.intactlabs.com/	info@intactlabs.com
Hy-SyEnce	USA	http://www.hy-syence.com/	info@hy-syence.info
Plant-e	Netherlands	www.plant-e.com	David.Strik @ plant-e.com

sequestration, GHG emission reductions and economic viability. The technologies mentioned herein are a small sample from a larger pool of technologies that are improving with time due to the dynamic nature of the bioelectrochemistry field.

10. Sensitivity analysis

The sensitivity to variations or uncertainties is significantly different for various process parameters [18]. In this paper, the simplified scenarios have been used to illustrate the concept of energy production and material movement within a BES, however, in practice the systems are much more complex and the outcome are governed by design, operational mode and materials used in the system.

Wastewater streams have the biggest potential in terms of economic viability while still being net energy positive and reduced GHG emissions. Solid wastes such as sludge, agricultural residues have moderate potential to be profitable, depending on the value of C offsets and feedstock collection and pre-processing costs. Already several start-up companies such as Trophos Energy (USA), Lebone (USA), IntAct Labs LLC (USA), Hy-SyEnce (USA), Plant-e (Netherlands) and Emefcy (Israel) based on MFC technology have been established and are trying to commercialize this technology (Table 4).

11. Conclusions

To conclude, a complete LCA is essential to implement the BES technology on a commercial scale. For this the following must be considered-

- Choice of functional unit – 1 kW/m^3 electrode compartment (for energy production); 1–10 kg COD/m^3 d (for wastewater treatment) and 1000 A/m^3 for product generation.
- Appropriate system boundary – BESs as 'microbial biorefinery' need to focus on energy generation and multiple products formation. This needs integrated process operation, reactor and component design.
- Co-products – Despite variability and uncertainty in technological and environmental performance for BESs, they promise to offer a positive energy gain and opportunity to reduce GHG emissions.

Acknowledgement

The research on bioelectrochemical systems at VITO is supported by a grant from VITO's strategic research fund under the project L2112.

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